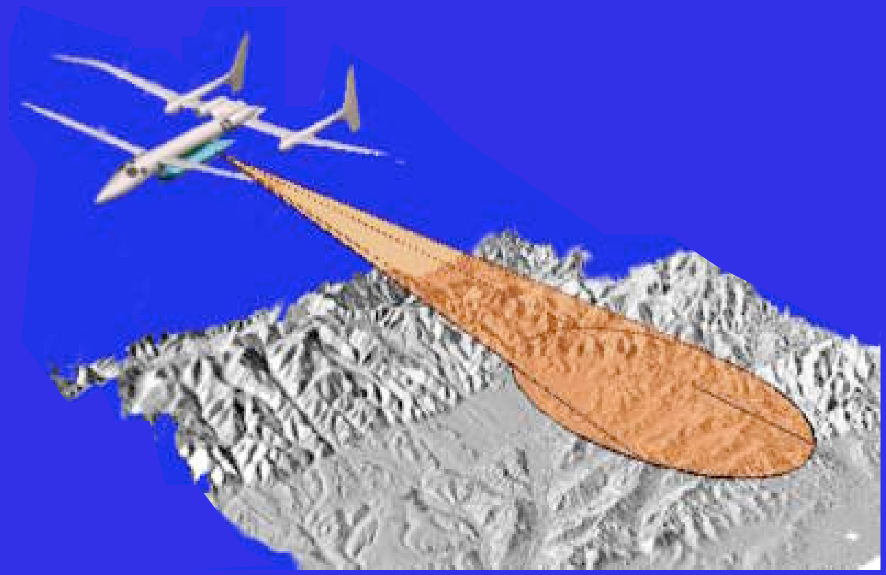
Status of a UAVSAR Designed for Repeat Pass Interferometry for Deformation Measurements



by

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ESTC Workshop - Palo Alto, California

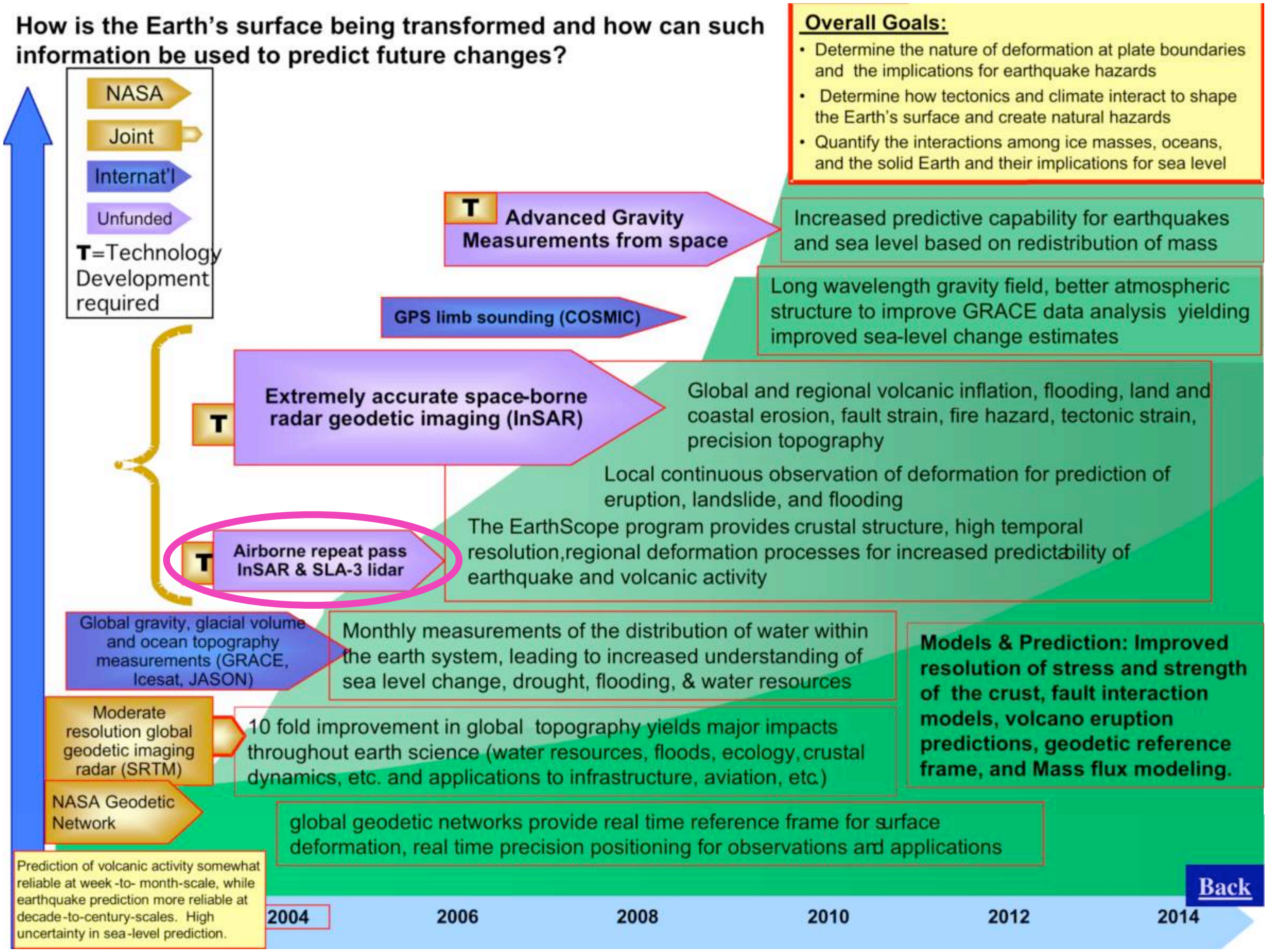
Historical Overview

- Spaceborne repeat pass radar interferometry derived deformation measurements has become a standard tool for the solid earth science and glaciological science communities.
  - Repeat times controlled by the the repeat orbit cycle of spaceborne SAR systems, e.g. ERS-1,2 (35 days), Radarsat (24 days), JERS (44 days), and Envisat (35 days).
  - Rapidly deforming features such as some volcanoes and glaciers or deformation from post seismic rebound require repeat times of a day or less to fully study the time varying nature of the deformation signal.
- Proposed an airborne radar interferometric repeat pass deformation capability as an augmentation to the NASA/JPL AIRSAR instrument for NASA 2002 Instrument Incubator Program Funding.
- Proposal was accepted, however NASA directed that the proposed capability be fielded on a UAV platform and that the first year effort be devoted to developing radar system design and implementation plan and that this plan be reviewed and concurred by the NASA science discipline program managers.

IIP Science Objectives

- The geophysical processes associated with natural hazards such as earthquakes and volcanoes occur over a wide range of temporal and spatial scales, and express themselves as subtle deformations in the Earth's crust.
- Present observational capabilities include sampling quickly varying surface change using *in situ* GPS methods, or observing fine spatial scale changes using interferometric synthetic aperture radar (InSAR).
- Generate fine resolution, accurate observations of crustal deformation resulting from natural hazards at hourly intervals.
  - Driven by slow plate motions, rapid injection of magma into the plumbing system of a volcano can lead to explosive eruptions over hours to days. Measurements from this system will lead to better models of the internal plumbing and magma flow within a volcano.
  - Steady slip along a fault in the crust can lead to sudden, major earthquakes and days of continuing slip. Using measurements from this system a better understanding and assessment of the the rate of slip and rebound surrounding a seismic event can be obtained.
- Additional science studies include rapidly moving glaciers and volumetric decorrelation studies in ice and vegetation.

NASA ESE Solid Earth Roadmap



Airborne InSAR is a critical component of the ESE roadmap

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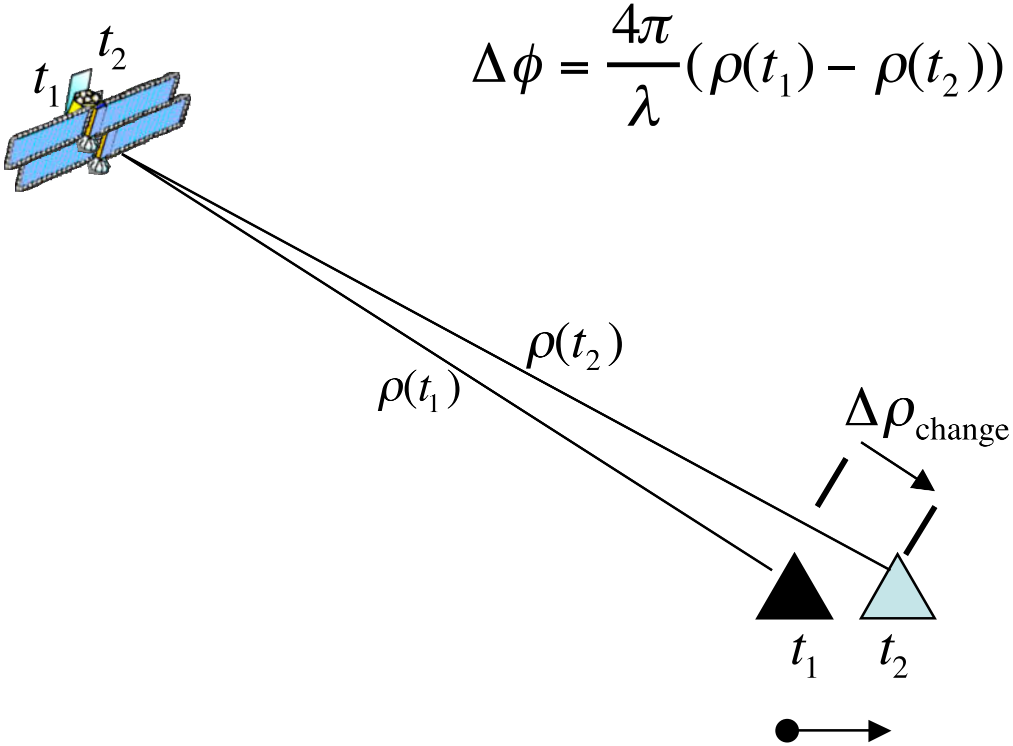
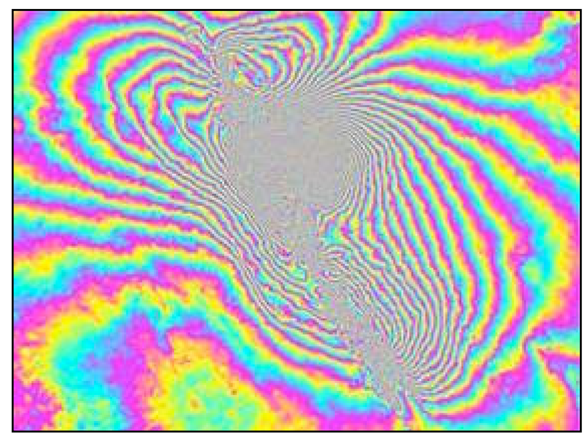
Deformation Interferometry

When two observations are made from the same location in space but at different times, the interferometric phase is proportional to any change in the range of a surface feature directly.

$$\Delta\phi = \frac{4\pi}{\lambda}(\rho(t_1) - \rho(t_2)) = \frac{4\pi}{\lambda}\Delta\rho_{\text{change}}$$





Surface Deformation of the 1999 Hector Mine Earthquake

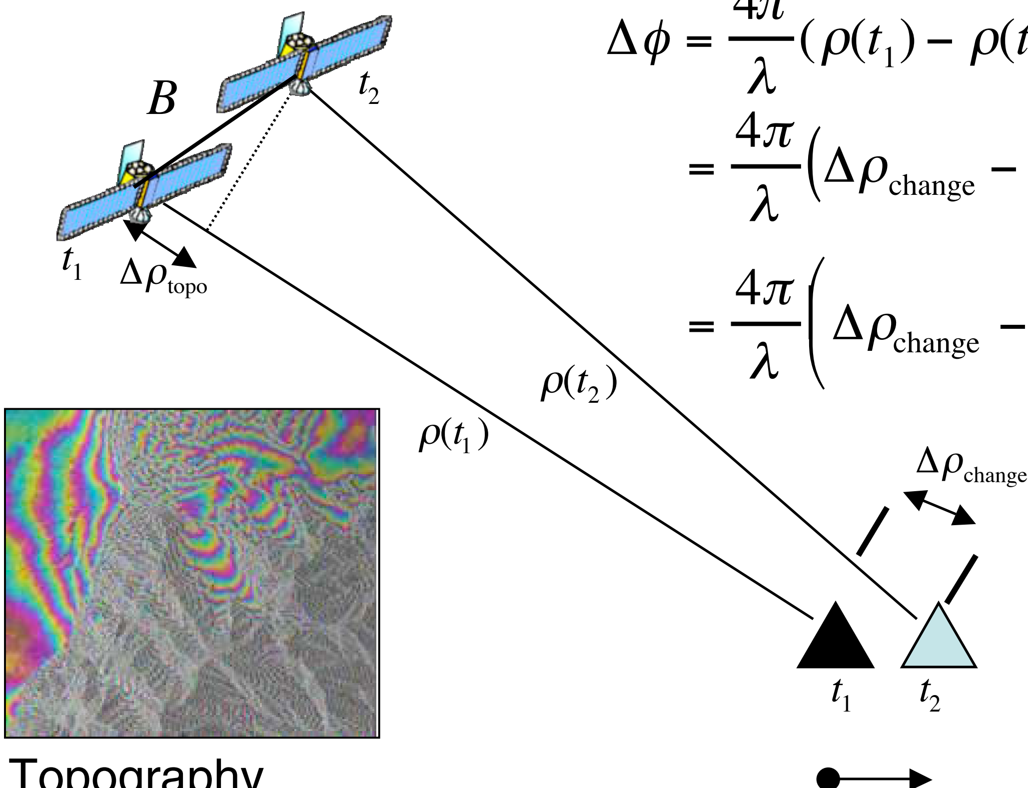
Deformation and Topography

Generally two observations are made from different locations in space and at different times, so the interferometric phase is proportional to topography and topographic change.

$$\Delta\phi = \frac{4\pi}{\lambda}\left(\rho(t_1) - \rho(t_2)\right) = \frac{4\pi}{\lambda}\left(\Delta\rho_{\text{change}} - \Delta\rho_{\text{topo}}\right)$$

$$= \frac{4\pi}{\lambda}\left(\Delta\rho_{\text{change}} - B\sin(\theta - \alpha)\right)$$

$$= \frac{4\pi}{\lambda}\left(\Delta\rho_{\text{change}} - B\cos(\theta_0 - \alpha)\frac{z}{\rho_0 \sin\theta_0}\right)$$

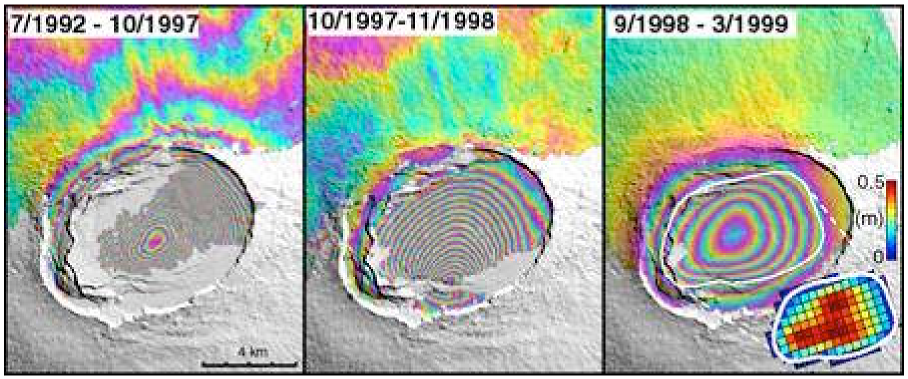


Topography can dominate

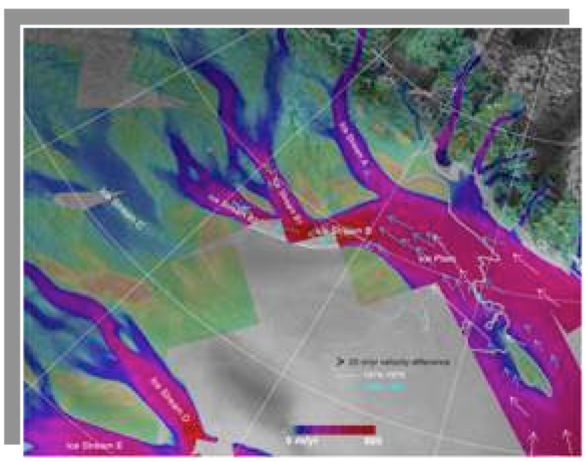
If topography is known, then second term can be eliminated to reveal surface change, but baseline must be small

The Role of Airborne InSAR

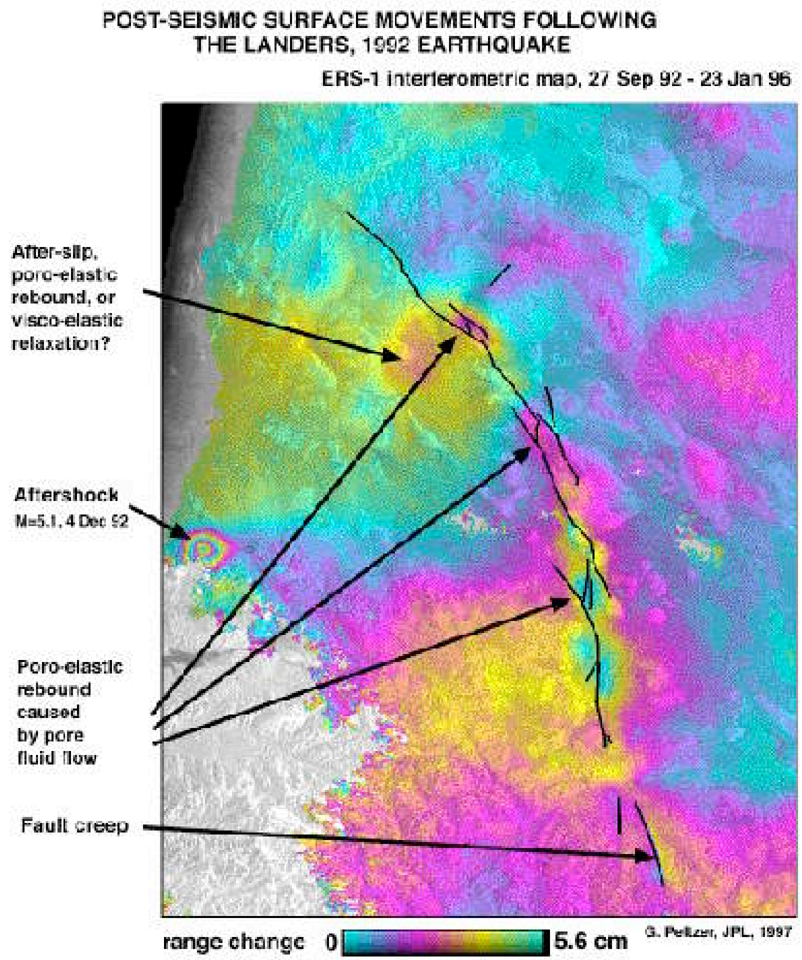
Airborne InSAR can contribute to local measurements of rapidly evolving surfaces



Evolution of volcanic magma chambers



Rapid evolution of ice



Post/Inter-seismic deformation

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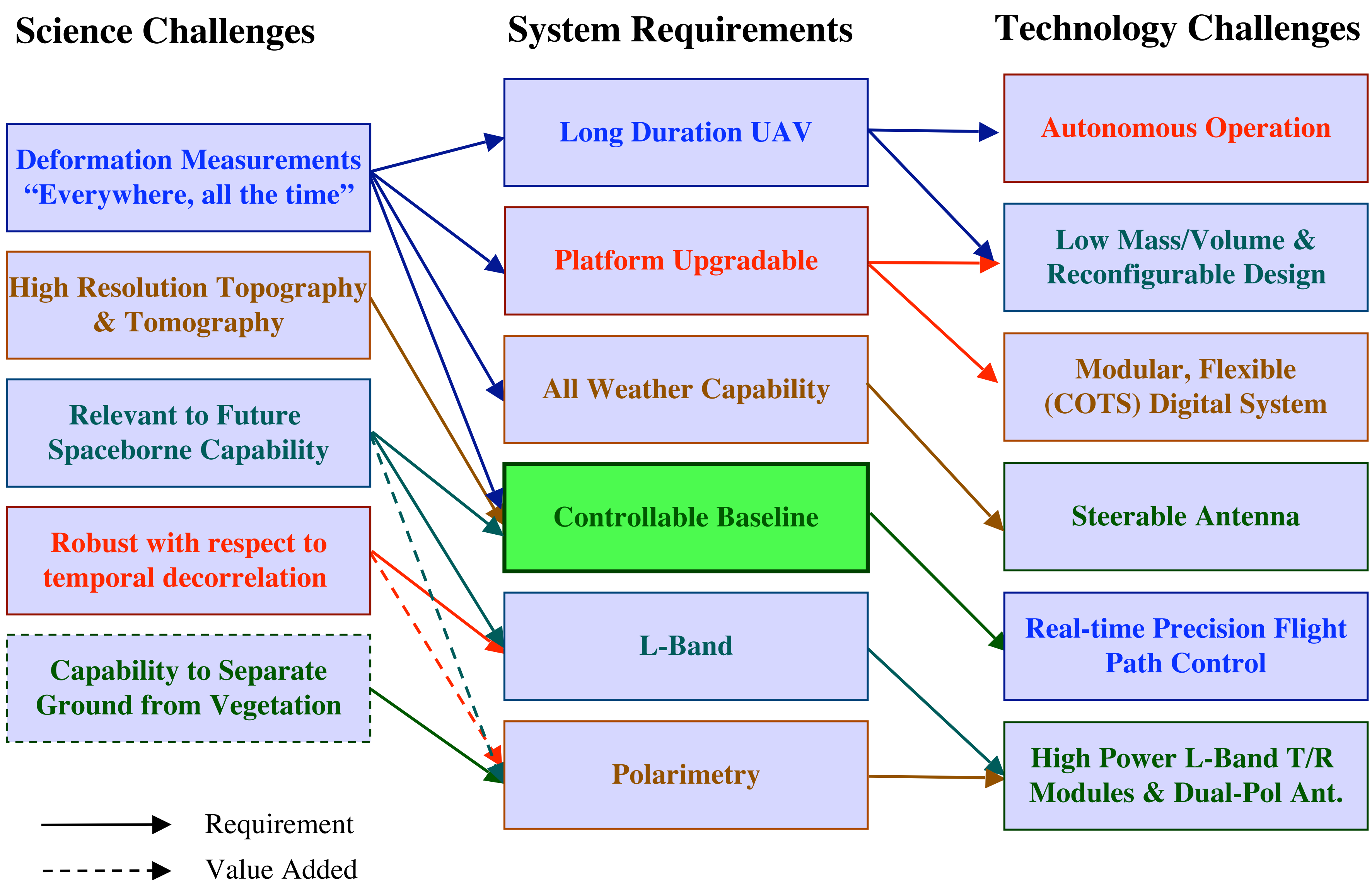
Science Imposed Platform and Instrument Constraints

- To reliably collect and process airborne repeat pass radar interferometric data for deformation measurements imposes additional platform and radar instrument constraints
  - The platform needs to fly within a 10 m diameter tube (with a 1 m goal).
    - Provides a small repeat pass baseline desired for repeat pass deformation measurements.
    - Provides ability to fly the same path multiple times with multiple time scales for reliable acquisition of desired science data.
    - Uses previously developed real-time GPS platform position determination capability (20-50 cm) that must be interfaced with the platform FMS (Flight Management System).
  - Radar should support electronic steering of antenna beam with 1° accuracy over a range of ±15° in azimuth so that the repeat pass pointing requirements can be achieved for a wide variety of wind conditions aloft.
    - Electronic steering of antenna must be linked to INU attitude measurements with an update rate capability of less than second.
    - L-band with maximal bandwidth of 80 MHz is required to maintain interferometric coherence over long time scales and have largest possible critical baseline.

Solid Earth Science and Technology Challenges



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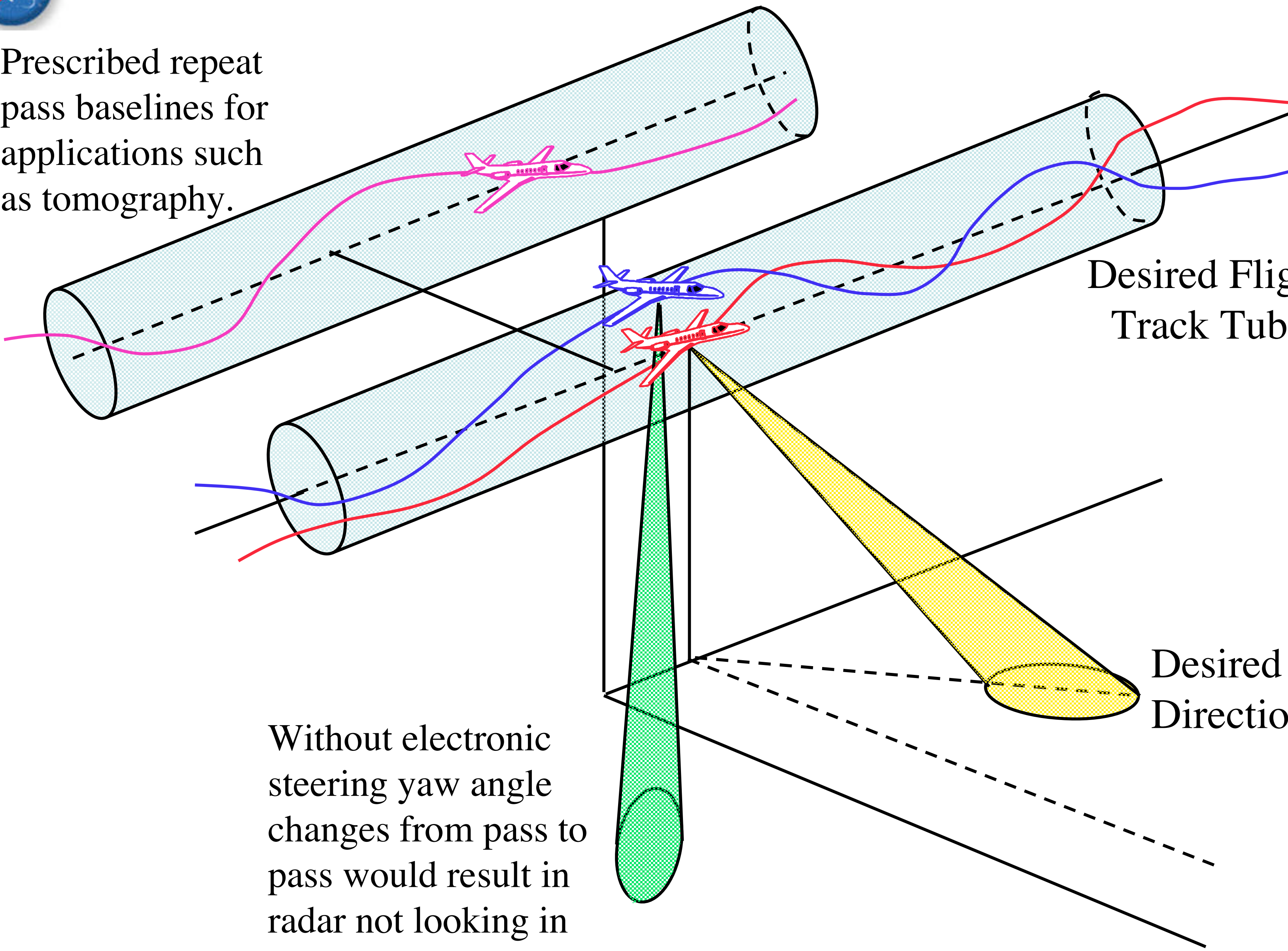
Solid Earth Science Requirement Traceability Matrix

Measurement Requirement	Engineering Requirement	Instrument/Platform Requirements
Deformation Accuracy 1 mm	**Interferometric Phase** 0.2°	**Phase Noise** < 1°
Temporal Correlation > 0.6	**Radar Frequency** L-band	**Antenna and Receivers** L-band Active Array
Temporal Baselines Hours→Years	**Pointing Accuracy** < 1/10 beamwidth	**Electronic Steering** ±15°azimuth / <1° step per PRI
Geometric Decorrelation & Stereo Displacement < .1 mm	**Baseline Error** < 10 m	**Avionics** Real-time GPS & Modern FMS
Observation Frequency Observation every 1-3 hrs for 48 hrs → weeks	**Ops Concept Supports Rapid Repeatability**	**Modularity** Transfer from Proteus to true UAV (e.g. Altair)
Along Track Misregistration < .1 pixel	**Baseline Stability** < 10^{-5} m/m change	**Avionics** Control Law Algorithm
Attitude Knowledge < 0.02° (all axes)	**Pointing Requirement** < 1/10 beamwidth	**Avionics/Radar** INU 1 Beam Steering
Spatial Resolution* 10 m	**Ground Resolution**† < 2 m	**Sampling Frequency**† > 80 MHz
Coverage Area > 1000 km^2	**Swath Width/Line Length** >10 km / 100 km	**Data Rate and Onboard Storage** 14 MHz / 1 TB

* after looks
† allows 5 range looks

Platform and Radar Constraints

Prescribed repeat pass baselines for applications such as tomography.



Desired Flight Track Tube

Desired Look Direction

Without electronic steering yaw angle changes from pass to pass would result in radar not looking in the same direction.

The Forgotten Term in the Differential Interferometric Phase

$$\phi = \frac{4\pi}{\lambda}\rho\left(\left[1-\frac{2\left(\langle\hat{l},\vec{b}\rangle-\langle\hat{l},\vec{D}\rangle+\frac{1}{\rho}\langle\vec{D},\vec{b}\rangle\right)}{\rho}+\frac{b^2+D^2}{\rho^2}\right]^{\frac{1}{2}}-1\right)$$

$$\phi \approx \frac{4\pi}{\lambda}\left(-\underbrace{\langle\hat{\mathrm{l}},\vec{\mathrm{b}}\rangle}_{\substack{\text{topo}\\\text{term}}}+\underbrace{\langle\hat{\mathrm{l}},\vec{\mathrm{D}}\rangle}_{\substack{\text{disp}\\\text{term}}}-\underbrace{\frac{1}{\rho}\langle\vec{\mathrm{D}},\vec{\mathrm{b}}\rangle}_{\substack{\text{forgotten}\\\text{term}}}\right)$$

$$\phi \approx \frac{4\pi}{\lambda}\left(\underbrace{\langle\hat{\mathrm{l}},\vec{\mathrm{D}}\rangle}_{\substack{\text{disp}\\\text{term}}}-\underbrace{\frac{1}{\rho}\langle\vec{\mathrm{D}},\vec{\mathrm{b}}\rangle}_{\substack{\text{forgotten}\\\text{term}}}\right)$$

Effect of Forgotten Phase Term on Measurements

$$\phi \approx \frac{4\pi}{\lambda}\left(\underbrace{\left\langle \hat{1}, \vec{D} \right\rangle}_{\substack{\text{disp}\\ \text{term}}} - \underbrace{\frac{1}{\rho}\left\langle \vec{D}, \vec{b} \right\rangle}_{\substack{\text{forgotten}\\ \text{term}}} \right) = \phi_{\mathrm{d}} - \frac{4\pi}{\lambda}\frac{1}{\rho}\left\langle \vec{D}, \vec{b} \right\rangle = \phi_{\mathrm{d}} - \underbrace{\frac{4\pi}{\lambda}\frac{1}{\rho}\mathrm{Db}\cos\beta}_{\phi_{\mathrm{for}}}$$

- If we want to keep the contribution from the forgotten term to the deformation signal below a specified threshold, $\Delta\rho_{\mathrm{thres}}$, then we have the following inequality must hold.

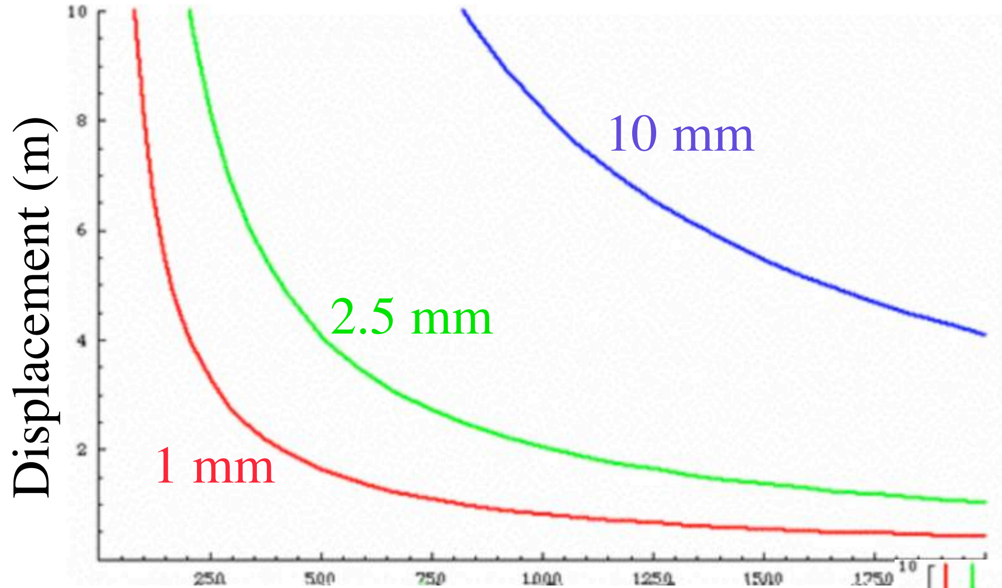
$$\phi_{for} \le \phi_{thres} = \frac{4\pi}{\lambda}\Delta\rho_{thres}$$

$$\frac{4\pi}{\lambda}\frac{1}{\rho}Db\cos\beta \le \frac{4\pi}{\lambda}\Delta\rho_{thres}$$

$$Db\cos\beta \le Db \le \rho\Delta\rho_{thres}$$

Maximal Displacement vs Baseline Length For Specified Error Levels

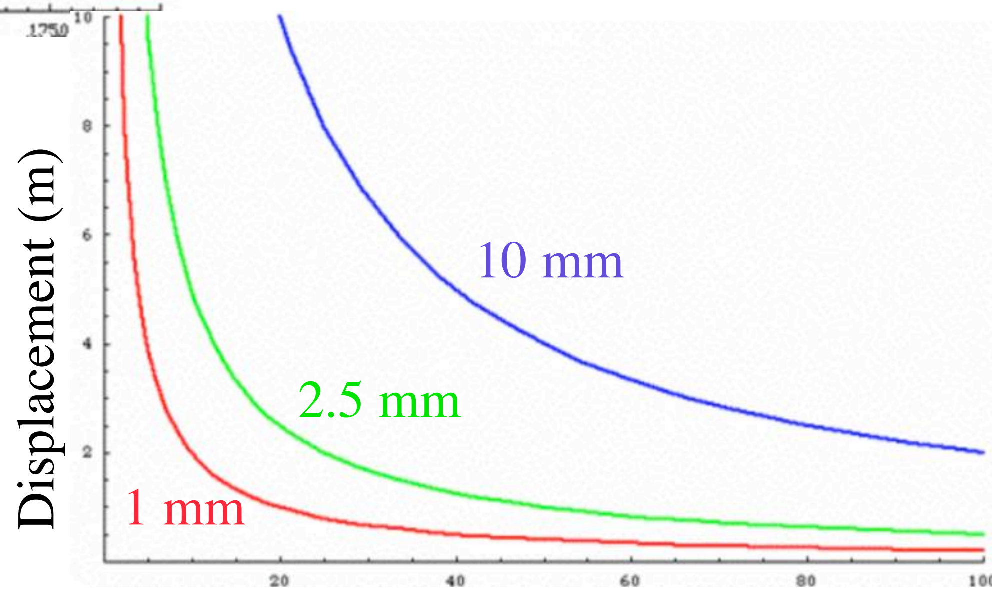
Spaceborne



- For the spaceborne case and geophysical signals of interest the "forgotten term" contributes negligibly to the signal.

Airborne

- The "forgotten term" puts additional constraints on the repeat pass baselines that are suitable for airborne repeat pass differential interferometry.



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Platform Requirements

- Operate in a variety of weather conditions
- Operate from conventional airports
- Operate above 12,000 meters to avoid commercial traffic and reduce turbulence
- Able to maintain a flight path with positional accuracy of ±5 meters
- Minimum range of 2000 nautical miles
- Minimum payload capacity of 300 kilograms
- Minimum payload volume of 1 cubic meter
- Minimum 2,000 watts of DC power available for the payload
- Support over-the-horizon up/downlink
- Able to mount an external, side-looking, active array antenna (0.5m by 2.0m) without obstruction

Preliminary Platform Comparison

Characteristic	ALTAIR	Proteus	Global Hawk
Availability	2 Purchased 0 Delivered Much Competition	One available on a first come first served basis	Still in development - anticipate unavailable for several years
Flight Cost	$3000/hr	$3300/hr	Unknown
FMS Modification	GPS Upgrade and Integration	GPS Upgrade, Pod and Autopilot	Unknown
Payload Weight Payload Volume Payload Power	340 kg 1.3 m^3 internal 4.5 kW	900 kg 17 m^3 pod 11.2 kW	900 kg ? ?
Range	5170 nmi	> 2000 nmi	14000 nmi
Ceiling	52000 ft	61000 ft	65000 ft
Operations	Crew of 7 in ground station	2 pilots, 1 crew chief	Unknown
Operational Limitations	FAA approval on a case by case basis	Piloted for takeoff and landing	Unknown

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Platform Selection Activity

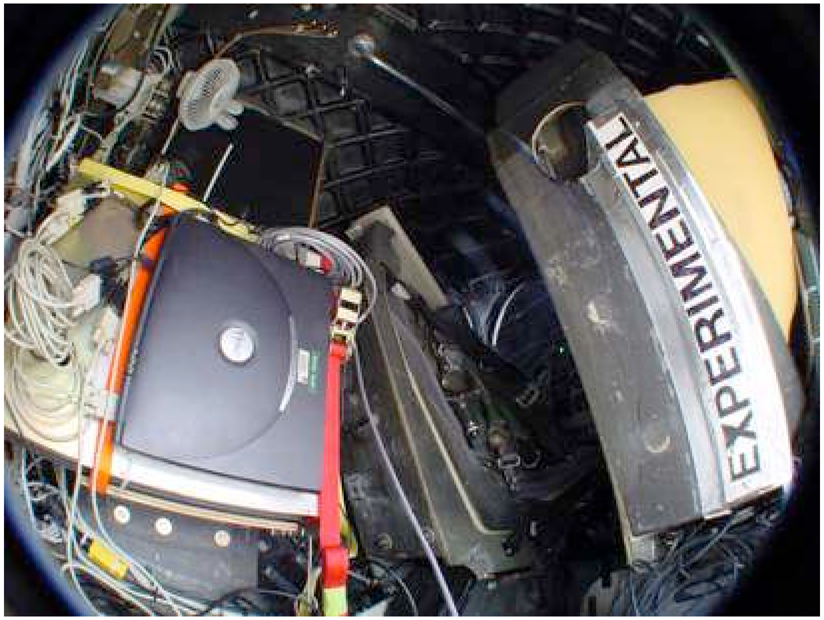
- **Navigation/Control:** Conducting studies to determine the ability of each platform to fly within the required tube of 10 m (and desired tube of 1 m).
  - Evaluate intrinsic capability of platform without modification to FMS system.
  - Evaluate ability of pilot to fly desired flight track with on course indication display in the cockpit.
    - Previous experience shows pilots unable to fly within tube.
    - Trying to maintain aircraft within tube is very taxing on the pilots and could not be maintained for long duration missions.
  - Assess ability of flying within the desired tube with modifications to the FMS.
    - Determine if software and/or hardware modifications are required to the FMS.
    - Modifications to support data ingest from real-time GPS determined state vectors.
    - Determine cost and schedule to modify FMS to meet desired flight path tracking accuracy.
- **Radar Instrument:** Study platform suitability for hosting an L-band radar and possible future upgrades to the system.

View of Proteus Aircraft Prior to Flight

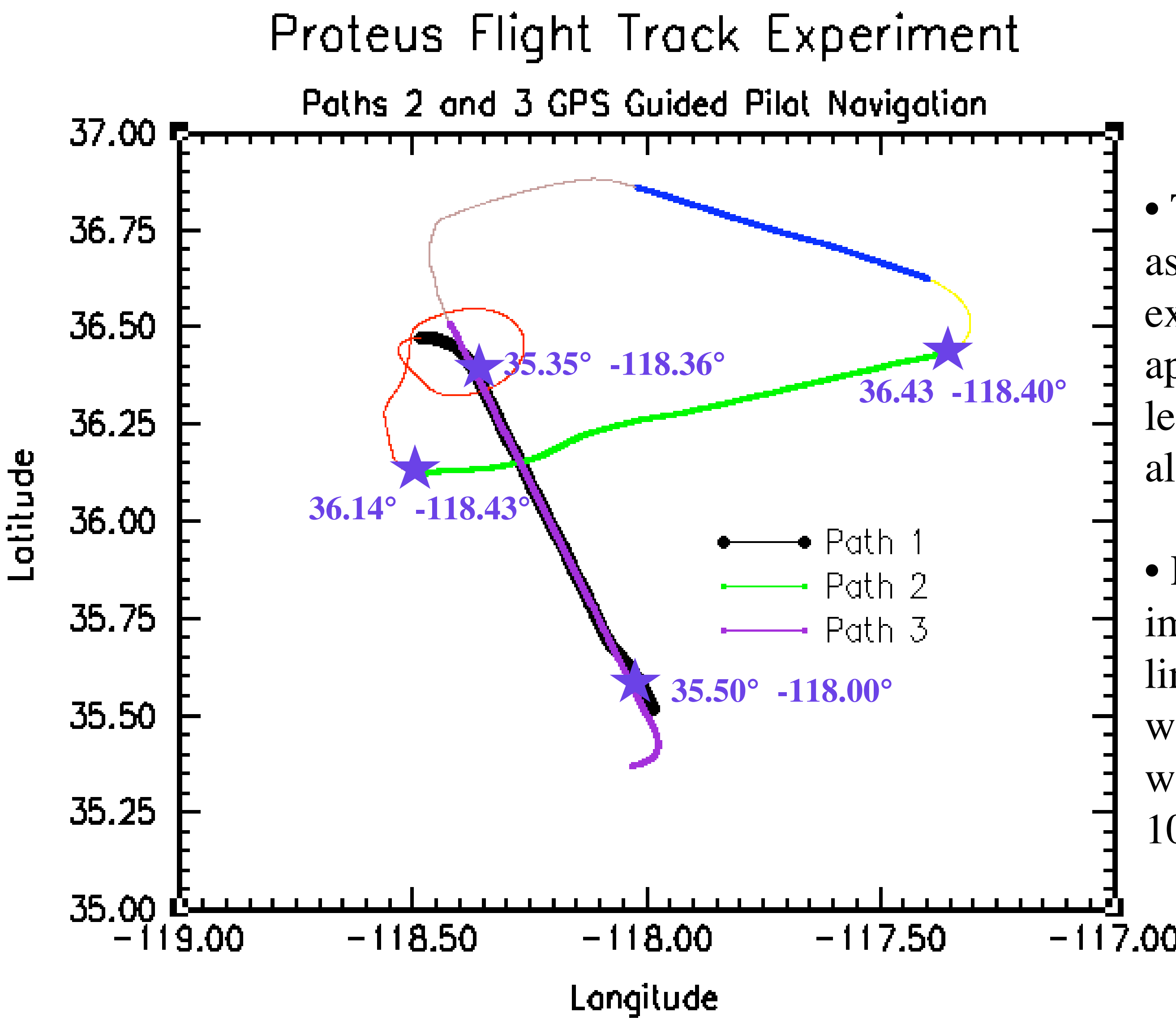
Profiles view of Proteus

Frontal view of Proteus

Interior Views of Proteus



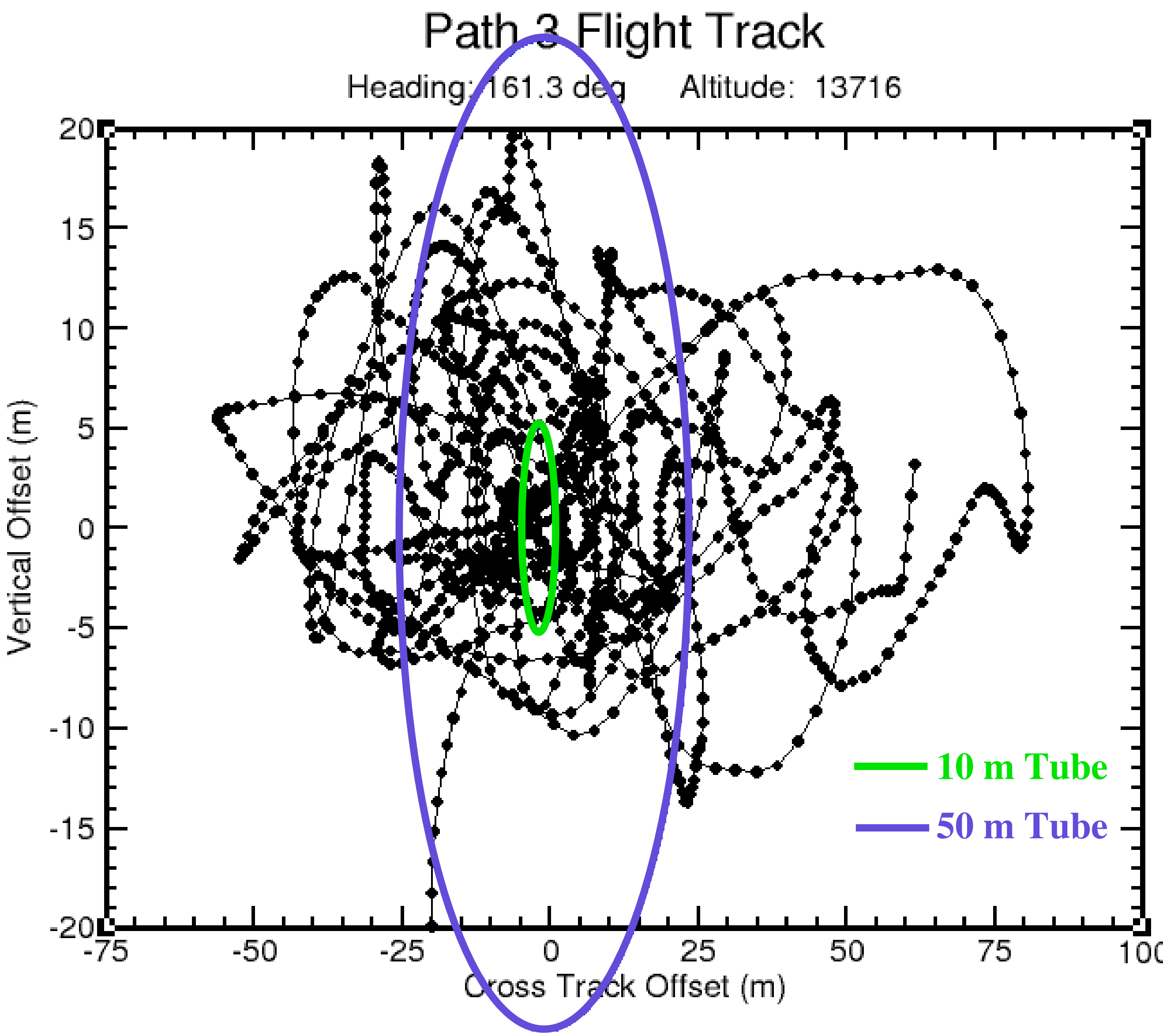
Flight Path as Flown in Flight Track Experiment



- Three tracks were flown as part of the flight track experiment. Each line was approximately 100 km in length and was flown at an altitude of 45000 ft (13716 m).

- Pilots showed progressive improvement on each flight line in their ability to stay within the tube, however they were not able stay within the 10 m tube desired.

Path 3 Cross Track and Vertical Offsets with Desired Flight Tube Overlaid



- The third pass was by far the best pass and was indicative of the pilots learning to fly the aircraft more effectively using the GPS navigation display.

- The pilots were much better able to maintain position within the 50 m tube, however most of the time the aircraft was outside the required 10 m tube.

Recommended Platform

•Because of airspace accessibility concerns to conduct the desired science missions and to reduce risk during the initial testing phase it is recommended that

–The near term transition platform for instrument development and mission operations be the **Proteus**.

–Using a universal pod approach will allow "easy" transition to an Altair when access to airspace issues have been resolved.

Proteus Aircraft

Recommended Platform

Operated by Scaled Composites in Mojave is a one-of-a-kind platform

ALTAIR UAV

Possible Future Host Platform

Enhanced Predator-B produced by General Atomics Aeronautical Systems, Inc. for NASA

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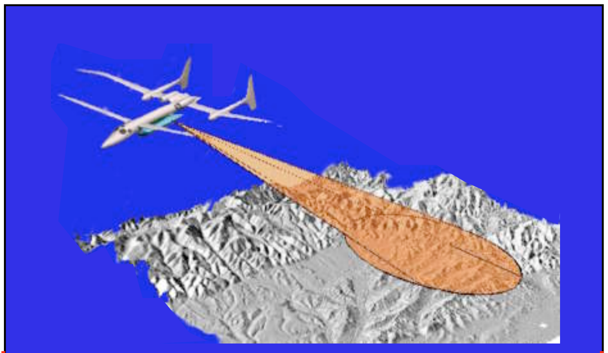
Radar Options

Increased Capability

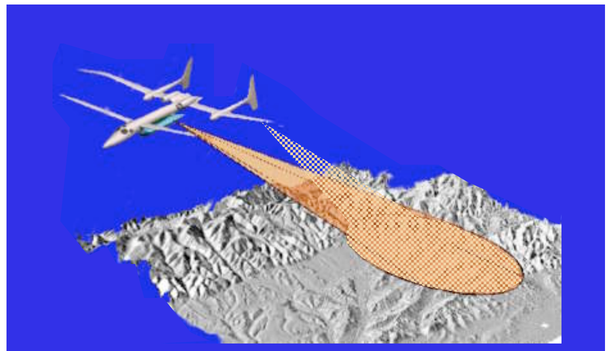
Increased Cost

Single Antenna L-band Polarimetric Radar



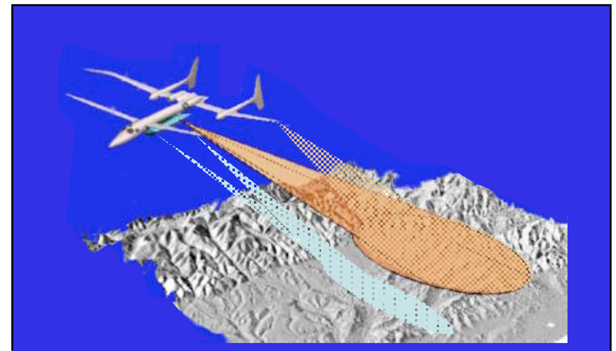
Repeat Pass Deformation
Land Cover Classification
Soil Moisture Studies
Geology

L-band Polarimetric-Interferometric Radar



Repeat Pass Deformation
Land Cover Classification
Soil Moisture Studies
Geology
Vegetation Structure
Hydrology

Dual Frequency L-band/(C,X,Ku)-band Polarimetric-Interferometric Radar



Repeat Pass Deformation
Land Cover Classification
Soil Moisture Studies
Geology
Vegetation Structure
Hydrology
Cold Land Processes
Ocean Studies

Increased Science Application

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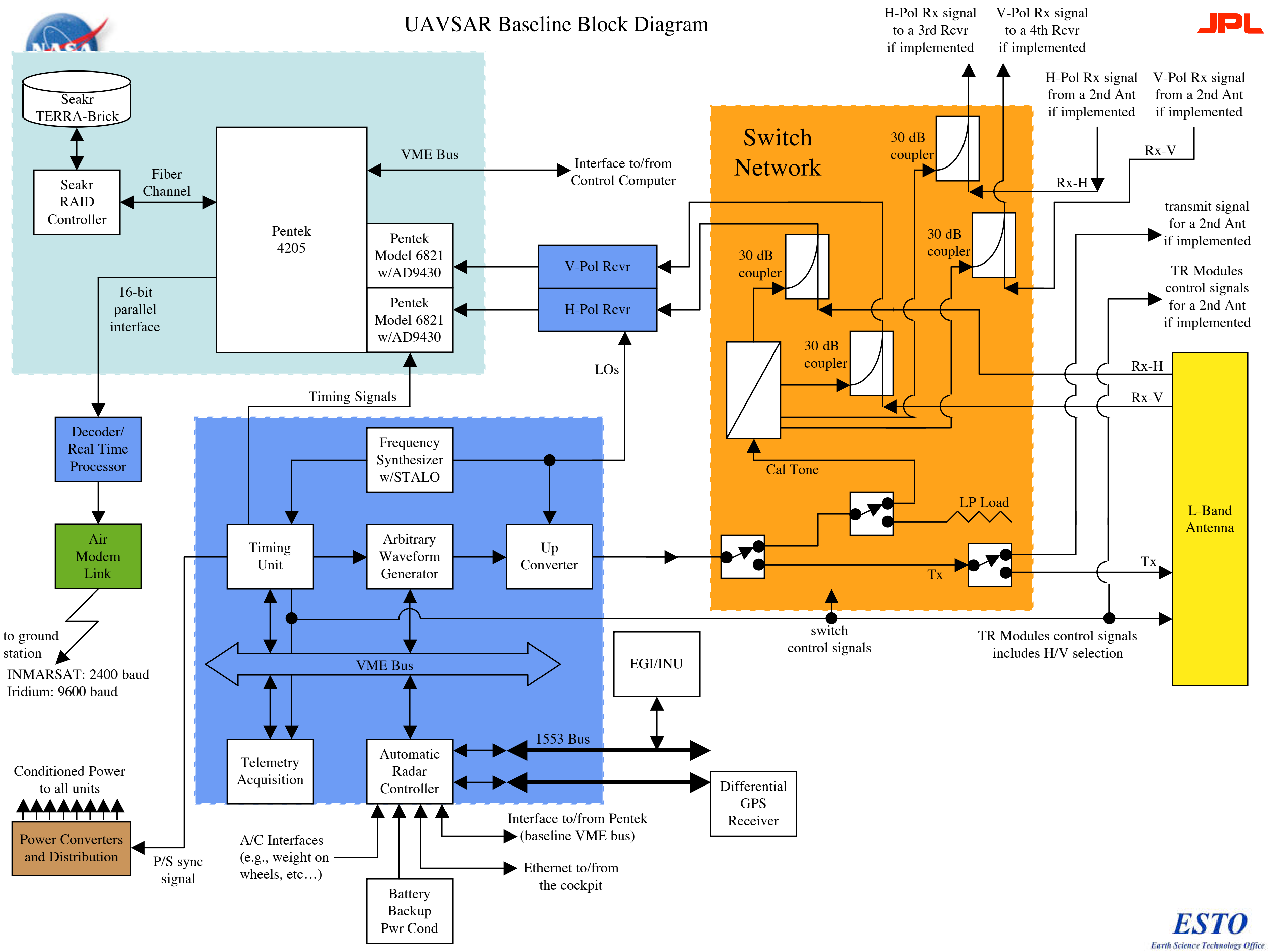
Radar Architecture

- Autonomous Operations
  - As this SAR will be operated on a UAV, there will be no Radar operators. Based on a data file provided by flight planning software, the UAVSAR will automatically initiate data takes at the appropriate locations throughout the flight. This approach was implemented on GeoSAR with good results.
- Built-In-Test (BIT) capability
  - Because of the autonomous requirement, this instrument must be able to perform BIT and determine failure at the unit level.
- Modularity
  - A modular approach to delineation of logic functions in the instrument will assist in addition of potential options in the future.
- Reconfigure-able
  - Because the instrument is designed for modularity, reconfiguration for the addition of potential options or installation on a different platform should be feasible.
- Multi platform capability
  - Goal is to be able to fly on either a ALTAIR or a Proteus aircraft.
- Plan to use a modified version of the AIRSAR Multi-Channel Advanced Digital System (MCADS) digital hardware in the UAVSAR instrument if possible.

Instrument Parameters

Parameter	Value
Frequency	L-Band
Bandwidth	80 MHz
Range Resolution	1.8 m
Polarization	Full Quad-Polarization
Bits in ADC	8 minimum/12 baseline
Waveform	Nominal Chirp/Arbitrary Waveform
Antenna Dimensions	.5 m range/1.5 azimuth
Azimuth Steering	±15°
Power	> 2.0 kW
Polarization Isolation	-30 dB

UAVSAR Baseline Block Diagram



Automatic Radar Control

- Flight planning software run on the ground prior to the flight will generate the necessary data files for both the aircraft navigation system (i.e., the autopilot) and the UAVSAR control computer.
- For the UAVSAR, this data file provides:
  - The necessary flight plan information for the control computer to understand where in the flight plan it is at any given point in time.
  - Operating mode and other control parameters for each data take.
  - Desired latitude, longitude and heading for each data take start.
  - Desired latitude and longitude for each data take stop.
  - Points in the flight where BIT should be performed.
- Based on data provided by the Inertial Navigation Unit (INU) in the instrument, the UAVSAR control computer knows where it is in the flight plan at all times.
- If the aircraft follows the flight plan correctly, the control computer initiates data takes and stops data takes based on the lat, long, and heading information from the INU.

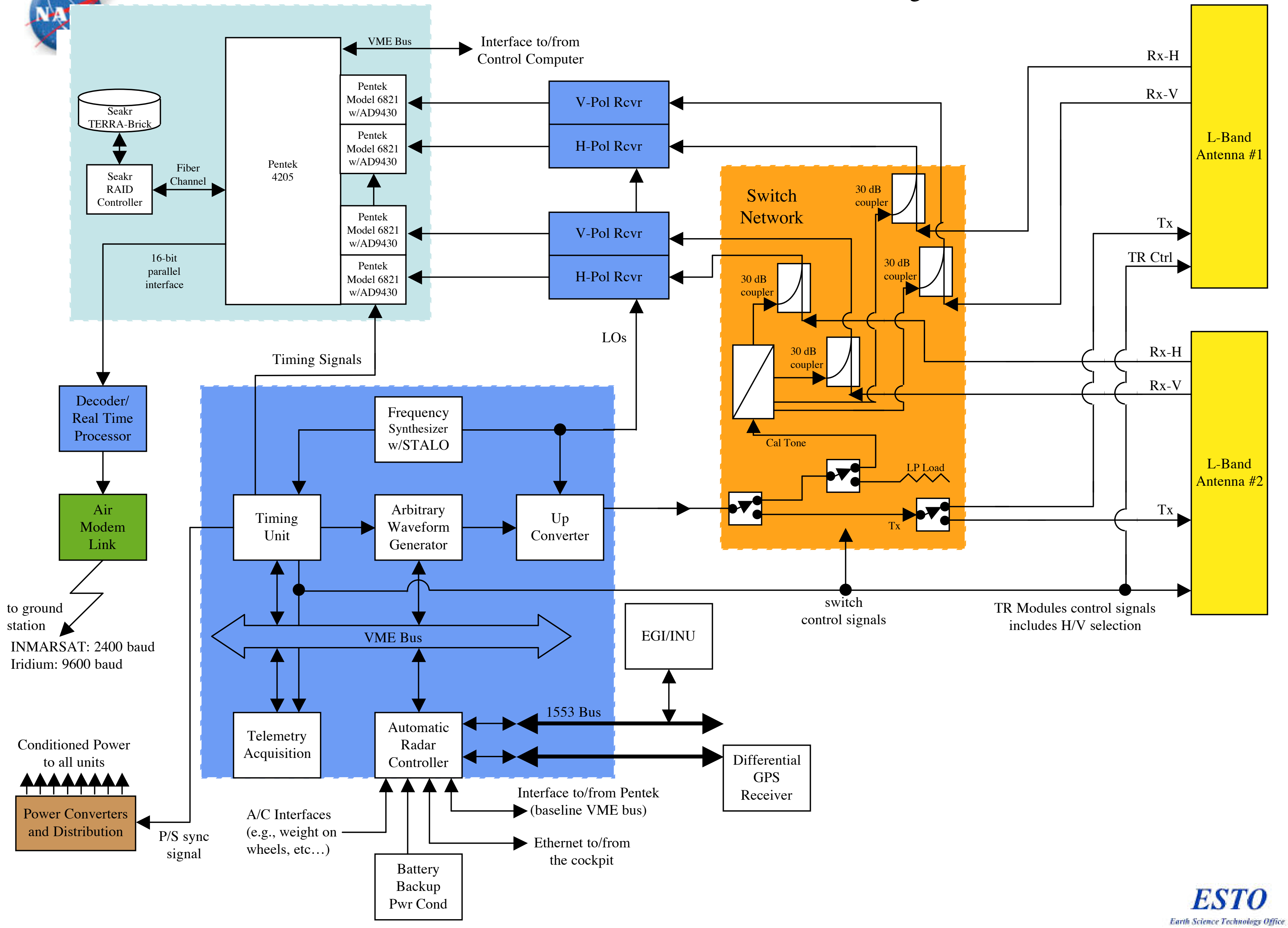
Built-in-Test Features

- In order to have a minimal ground crew and facilitate maintenance at remote locations this instrument must be able to perform BIT and determine failure at the unit level.
- The BIT would be performed prior to take off, to verify that the instrument is fully operational.
- Data in the flight plan file provided to the control computer would indicate when to periodically perform BIT during the flight .
- The BIT would be performed just after landing, to verify that the instrument is still fully operational.
- Data acquired for all these tests would be compared for trend analysis and problem identification.

Alternate Configurations

- With some relatively minor hardware changes, the UAVSAR could be modified to add an interferometric capability.
- The addition of a second (identical) antenna on the aircraft would be the only significant item with the main impacts from increased antenna costs and potential aircraft modification issues.
- Other hardware changes for interferometry would be the addition of some extra switches in the switching network, and the necessary timing signals for controlling these switches .
- If the timing signals for supporting interferometry were designed into the timing unit initially, then it would just be a matter of later routing the necessary signals to the correct switches.
- The necessary additional switches for supporting interferometry could be designed into the switching network initially, and either implemented when the unit is built or added sometime later if desired.
- These changes would be able to support either along-track or cross-track interferometry equally well.

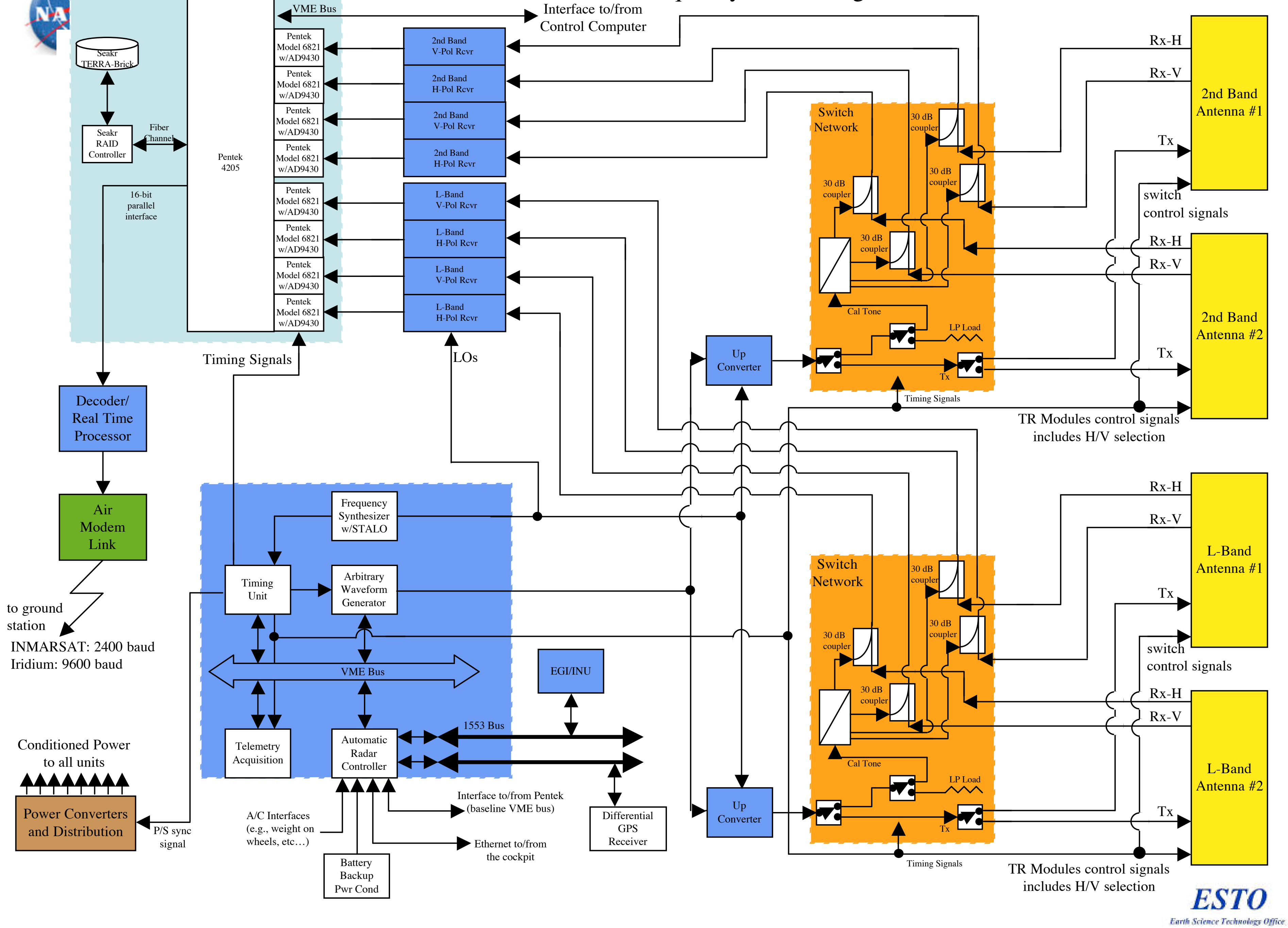
UAVSAR Cross Track Interferometer Block Diagram



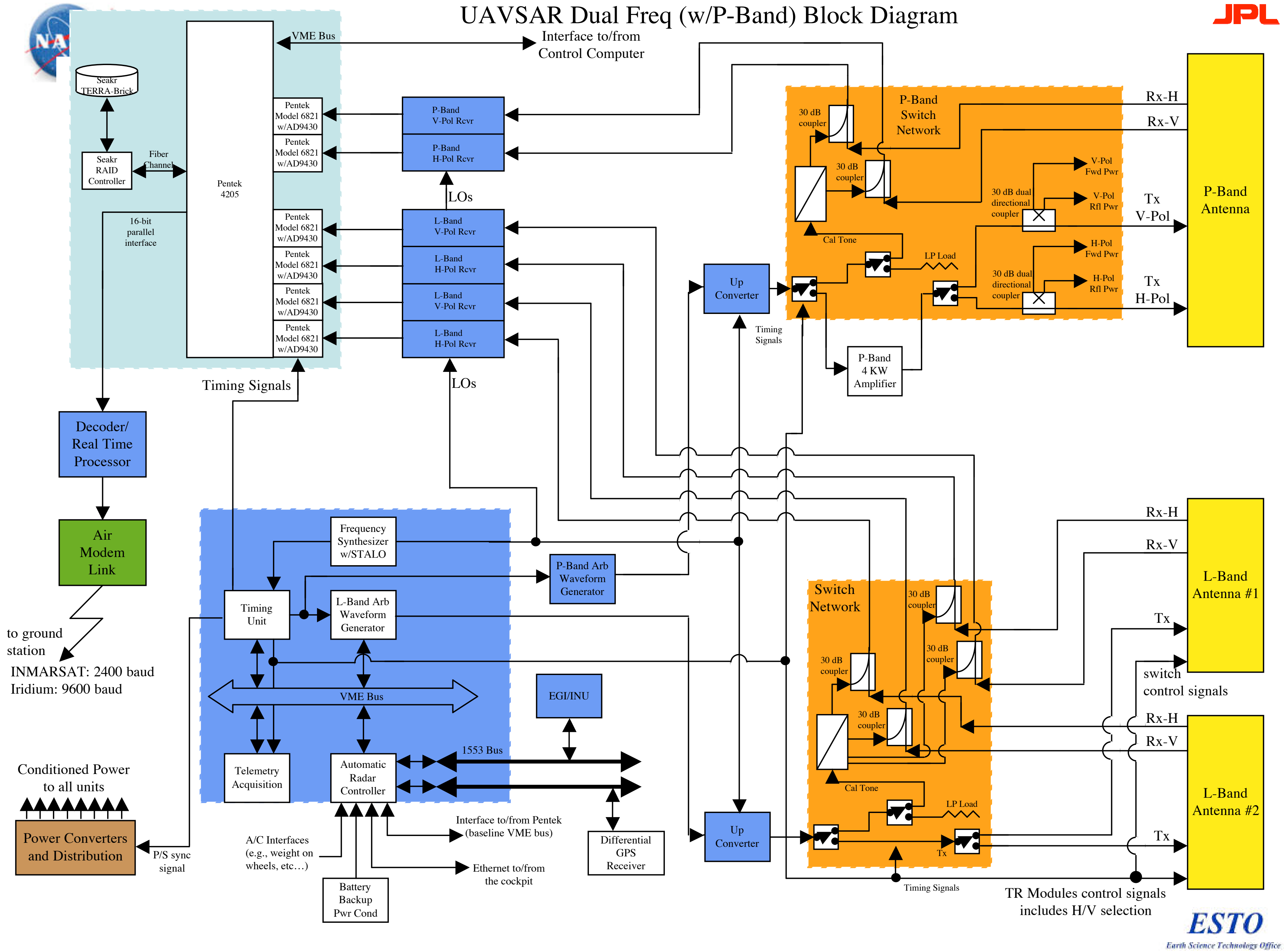
Dual Frequency Option

- The addition of a second frequency radar would be more involved than the addition of an interferometric capability.
- For the second frequency Radar, it would be necessary to add:
  - An additional Up-Converter unit.
  - An additional Switching Network.
  - An additional antenna panel.
  - A pair of additional receivers for down-conversion.
  - A pair of additional digital channels to the MCARS system.
- This option could be implemented in the Proteus aircraft without modifying the anticipated mechanical packaging approach.
- In order to implement this option in the Predator-B aircraft, it is quite possible that a more efficient mechanical packaging approach would need to be pursued. This type of mechanical packaging approach has not been pursued thus far.

UAVSAR Dual Frequency Block Diagram



UAVSAR Dual Freq (w/P-Band) Block Diagram



Solid-State Active Array

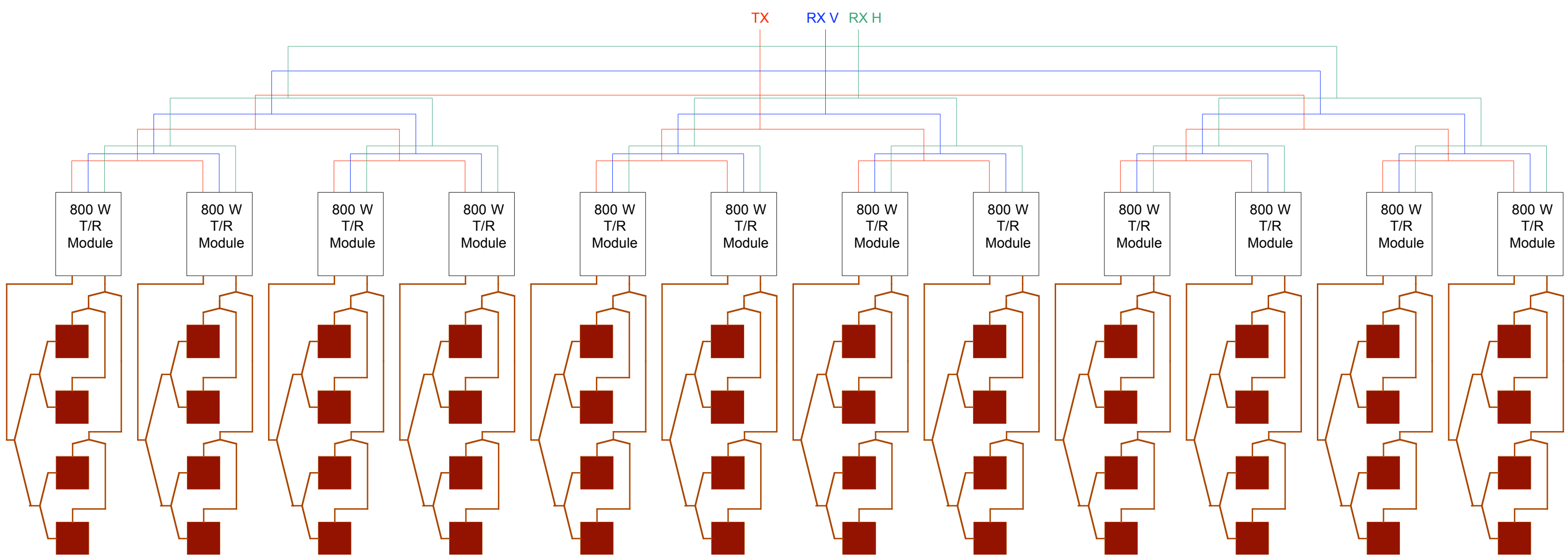
Antenna Description

- Dual-polarized microstrip patch antenna
  - 1.5 m x 0.5 m (12 x 4 elements)
- Each column of four elements fed by one transmit/receive (T/R) module
- T/R module:
  - 800 W transmitter
  - Transmit polarization select switch
  - Two receivers for simultaneous H and V polarization
  - Phase shifters for beam steering

Specifications

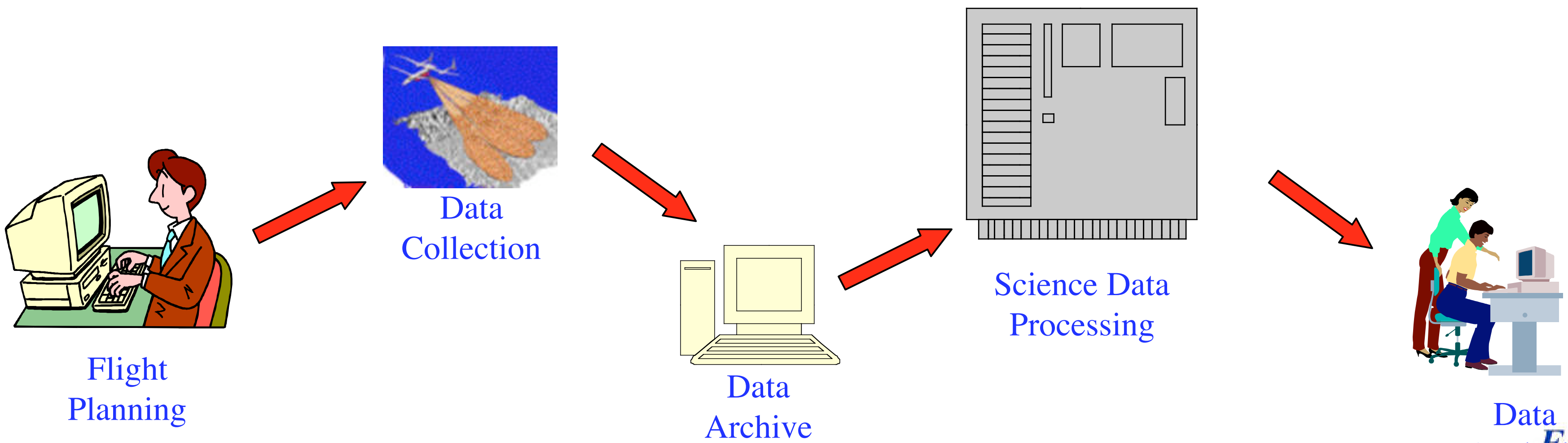
- Frequency: 1.22-1.30 GHz
- Azimuth steering range: ± 15°
- Transmit:
  - H or V polarization
  - 9.6 kW peak power
  - 10% duty cycle, max
  - Pulse width 1 ms, max
- Receive:
  - Simultaneous H and V polarization
  - Receive noise figure < 3 dB

Antenna Block Diagram

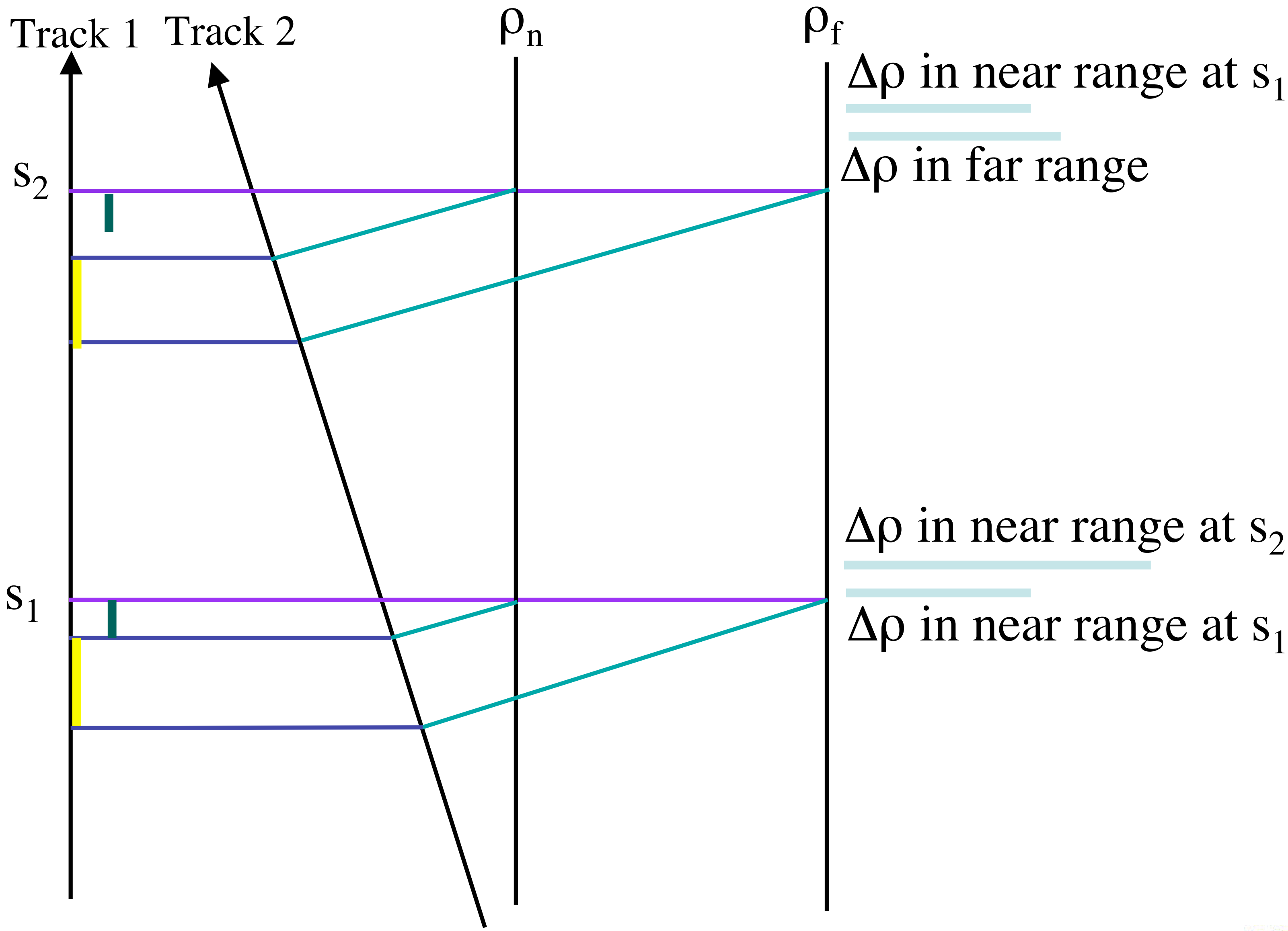


Ground Data System Description

- The ground data system will be a modified version of the Jurassicprok processor developed for the GeoSAR program. Elements include
  - MMP: Motion measurement processing software which took motion and metrology data and generated motion data for the processor as well as the command file for the signal processor.
  - Jurassicprok: Raw signal to height map interferometric SAR processor that incorporates the latest processing algorithms.
  - A set of calibration codes for interferometric and radiometric calibration.
  - Diagnostic tools for analyzing and quantifying system performance.
  - RFI: Code for removing unwanted radio interference from the raw data.
  - Flight Planning Software: Software for planning radar instrument flight lines and radar commands.
- Several modifications to the existing set of software will be required to support UAVSAR and its planned applications.



Offsets and Baseline Geometry



Basic Equations - Along Track Offsets

- Further simplification requires that one recognize that the expression multiplying the tan(β) term is b_c. Using the figure on the next viewgraph and some small angle approximations and a little algebra yields

$$\Delta s_T = \rho_2 \sin\left(\theta_{\ell_2}\right)\frac{\partial b_c}{\partial s} - \rho_2 \cos\left(\theta_{\ell_2}\right)\frac{\partial b_h}{\partial s} + b_c \tan(\beta)$$

where we have again made use of the identities

$$\tan(\eta) = \frac{\partial b_c}{\partial s} \qquad \tan(\theta_p) = \frac{\partial b_h}{\partial s}$$

Simple Model for Airborne Offset Field

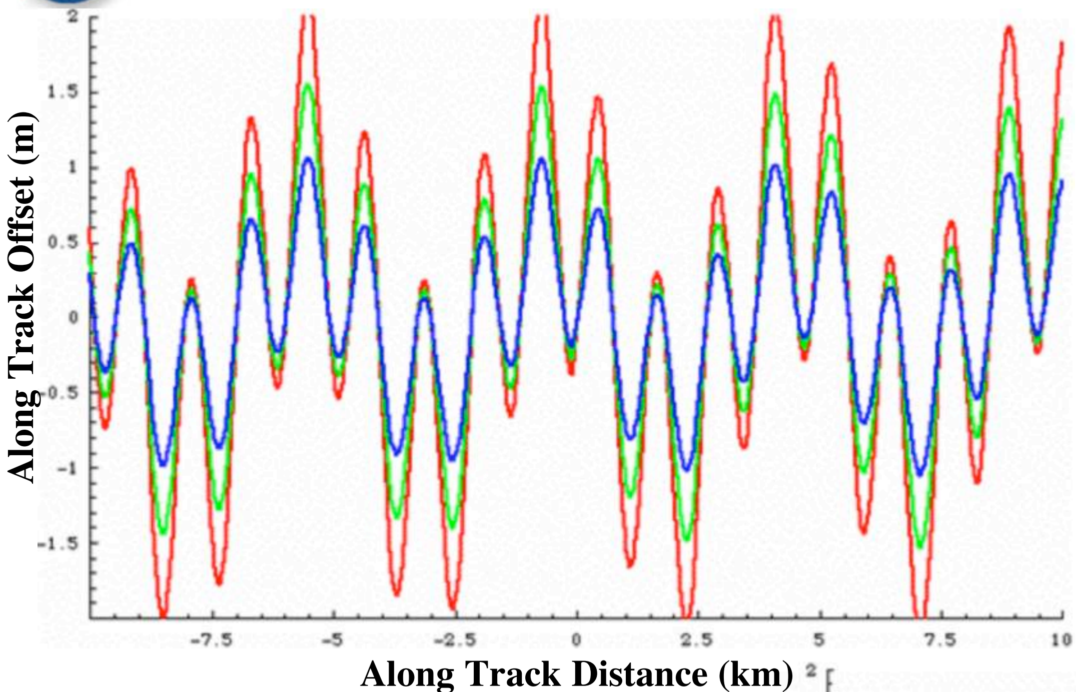
$$\Delta b_c(s) = \sum_{i=1}^{N_c} a_i \sin\left(\frac{2\pi}{L_i} + \phi_i\right) \qquad \Rightarrow \qquad \frac{\partial \Delta b_c}{\partial s}(s) = \sum_{i=1}^{N_c} a_i \frac{2\pi}{L_i} \cos\left(\frac{2\pi}{L_i} + \phi_i\right)$$

$$\Delta b_h(s) = \sum_{j=1}^{N_h} b_j \sin\left(\frac{2\pi}{M_j} + \psi_j\right) \qquad \qquad \frac{\partial \Delta b_h}{\partial s}(s) = \sum_{j=1}^{N_h} b_j \frac{2\pi}{M_j} \cos\left(\frac{2\pi}{M_j} + \psi_j\right)$$

- Very small relative displacements yield appreciable displacements along track displacement relative to the along track pixel size.

$$a_i \geq \frac{k_{thres} \Delta s_{pix} L_i}{2\pi c_{xt}} \quad , \quad b_j \geq \frac{k_{thres} \Delta s_{pix} M_j}{2\pi h_p}$$

Example Along Track Displacements

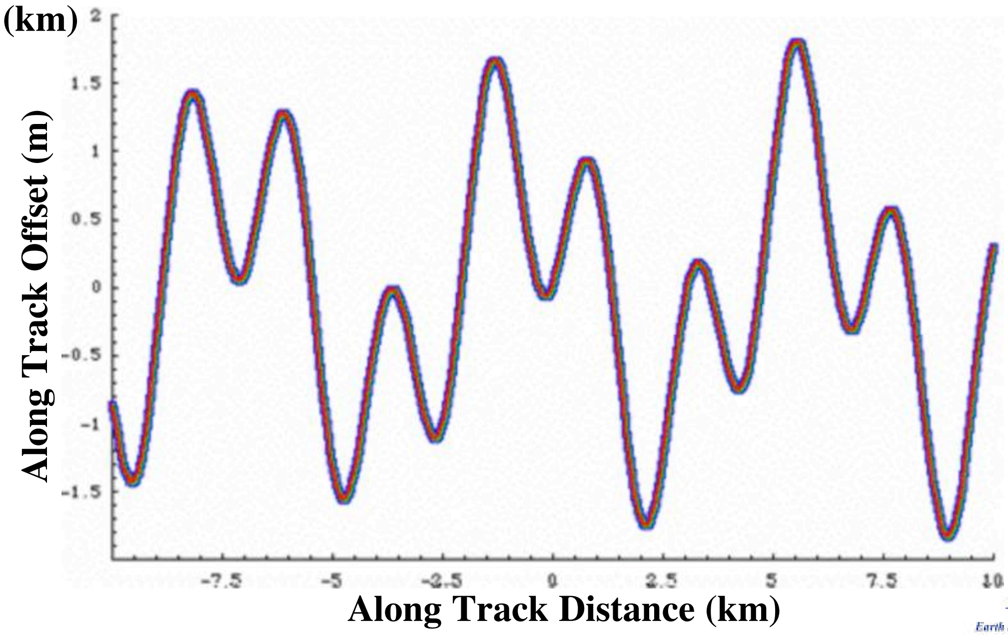


Horizontal Baseline

a_i = .05 m , .012 m
L_i = 5000 m , 1200 m

Vertical Baseline

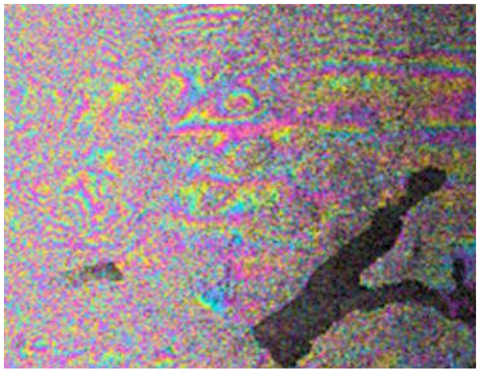
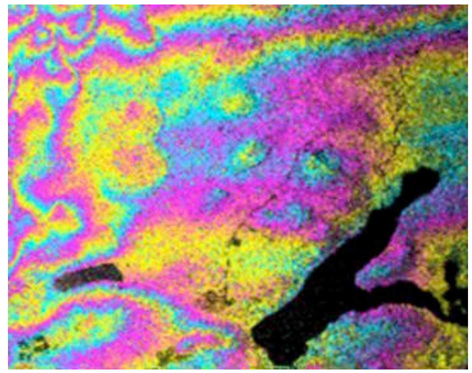
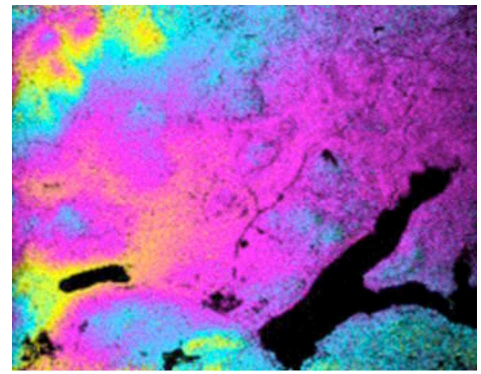
b_j = .075 m , .025 m
M_j = 6500 m, 2300 m



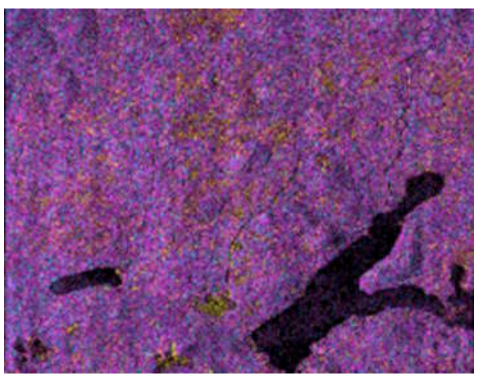
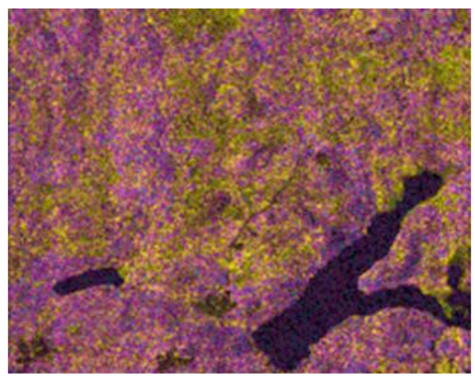
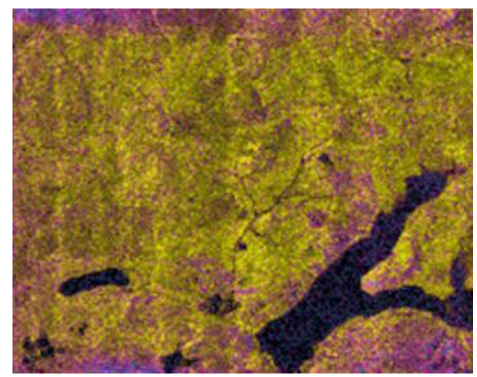
Airborne Repeat Pass InSAR Experience

Airborne InSAR experiments have been attempted using AIRSAR

Interferograms

C-band **L-band** **P-band**

Correlations

Issues: Repeatability, Controllability, Platform Availability